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RISK-BASED ANALYSIS FOR CORPS FLOOD PROJECT STUDIES - A STATUS REPORT

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ABSTRACT

The Corps of Engineers now requires risk-based analysis in the formulation of flood damage reduction projects. This policy is a major departure from past practices and is viewed as a significant step forward in improving the basis for Corps project development. The risk-based approach explicitly incorporates uncertainty of key parameters and functions into project benefit and performance analyses. Monte Carlo simulation is used to assess the impact of the uncertainty in the discharge-probability, elevation-discharge, and elevation-damage functions. This paper summarizes historical project development study methods, describes the risk-based analysis approach, presents application results, and discusses project design implications of the new policy.

INTRODUCTION

Studies involved in the development of flood damage reduction projects traditionally applied best estimates of key variables and other data elements in determining project benefits and performance. Benefit calculations involve discharge-probability, elevation-discharge (or rating),

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and elevation-damage functions and costs associated with the proposed project over it's life. Historically, inherent errors and imprecisions in these data were acknowledged but not explicitly incorporated into the analysis or considered in the results. Uncertainty was normally addressed through sensitivity analysis, conservative parameter estimates, and addition of extra capacity such as freeboard for levees. Each has limitations in estimating the statistical implications of uncertainty.

Project performance traditionally considered level-of-protection as the primary performance indicator. It is the exceedance probability of the event that corresponds to the capacity of the project. The importance of this single indicator was often overemphasized, while ignoring other performance information needed to insure proper project comparisons in selecting the alternative to be recommended for implementation. Project selection and recommendations were generally based on maximizing net National Economic Development benefits.

RISK-BASED ANALYSIS APPROACH

Corps' policy now requires application of risk-based analysis in the formulation of flood damage reduction projects [1]. Risk-based analysis quantifies the uncertainty in discharge-probability, elevation-discharge, and elevation-damage relationships and explicitly incorporates this information into economic and performance analyses of alternatives. The process requires use of Monte Carlo simulation [2], a statistical sampling-analysis method that is used to compute the expected value of damage and damage reduced, while explicitly accounting for uncertainty.

The method for development of discharge-probability relationships depends on data availability. For gaged locations and where an analytical fit is appropriate, the method defined by Bulletin 17B [3] is applied. Uncertainties for discrete probabilities are represented by the non-central *t* distribution. For ungaged locations, the discharge-probability function is adopted from applying a variety of approaches [4]. When justified, curve fit statistics for the adopted function are computed. An equivalent record length is assigned based on the analysis and judgements about the quality of information used in adopting the function. Regulated discharge-probability, elevation-probability, and other non-analytical probability functions require different methods. An approach referred to as 'order statistics' [5] is applied to develop the probability function and associated uncertainty for these situations.

Elevation-discharge functions are developed for index

locations from measured data at gages or from computed water surface profiles. For gaged data, uncertainty is calculated from the deviations of observations from the best fit rating function. Computed profiles are required for ungaged locations and for proposed project conditions that are modified from that of historic observations. Where sufficient historic data exists, profile uncertainty is estimated based on the quality of the computation model calibration to the historic data. Where data are scant, or the hydraulics of flow complex, such as for high velocity flow, debris and ice jams, and flow bulked by entrained sediments, special analysis methods are needed. One approach is to perform sensitivity analysis of reasonable upper and lower bound profiles and use the results to estimate the standard deviation of the uncertainty in stage. Unless data indicate otherwise, the uncertainty distribution for flow-stage functions is taken to be Gaussian [6].

Elevation-damage functions are derived from inventory information about structures and other damageable property located in the flood plain. The functions are constructed at damage reach index locations where discharge-probability and elevation-discharge functions are also derived. Presently, separate uncertainty distributions for structure elevation, structure value, and content values are specified and used in a Monte Carlo analysis to develop the aggregated structure elevation-damage function and associated uncertainty. The uncertainty is represented as a standard deviation of error at each elevation coordinate used for defining the aggregated function at the index location.

CHESTER CREEK EXAMPLE

Chester Creek is a 177 km^2 watershed located near Philadelphia, PA. In this example, simulated project studies are performed to determine feasibility of implementing several flood damage reduction plans. This includes comparison of the economic value, performance, and other factors for with- and without-proposed project conditions. Future conditions are projected to be similar to the base year of project implementation. Plans evaluated are 7 and 8 m. high levees, a channel modification configured with 15 m. bottom and 43 m. top widths, and a detention storage project of 5.5 million m^3 capacity.

Without-project condition discharge-probability is derived using Bulletin 17B [3] guidelines. The stream gage located in the basin has a 65 year record length. Confidence limits for the discharge probability function are computed based on the statistics of the gaged record and streamflow record length. The rating curve at the index location is developed from a computed water surface profile. Rating uncertainty is derived from study of calibration

results using high water marks and sensitivity analysis. The standard deviation of uncertainty error varies from zero at no discharge to one foot for .01 probability discharge and beyond. Uncertainty in damage is taken as the standard deviation value equal to 10% of the damage value. For with project conditions, revised functions and associated uncertainties are developed.

Monte Carlo simulations develop expected annual flood damage and performance information for with- and without-project conditions. A summary of economic results are shown in Table 1. The display format is similar to that used historically. The results are different from that which would be generated from traditional analysis - but not dramatically so. Inclusion of benefits other than damage reduction benefits shown here could alter the study conclusions to a small degree.

Any of the alternatives with positive net benefits is a candidate for recommendation for implementation. All but the detention storage alternative meets this test. The 8 m. high levee is identified as the plan that maximizes national economic development. It also provides the greatest benefits and is the most costly plan.

Table 1. Results of economic evaluation

Plan description	Annual with-project residual damage in $1,000	Annual with-project inundation reduction benefit in $1,000	Annual cost in $1,000	Annual net benefit in $1,000
W/out Project	78.1	0.0	0.0	0.0
7 m.levee	50.6	27.5	19.8	7.7
8 m.levee	18.4	59.7	37.1	22.6
Channel	41.2	56.9	25.0	11.9
Detention	44.1	34.0	35.8	-1.8

Performance information is shown on Table 2. Expected annual exceedance probability is similar to the traditional level-of-protection except that uncertainty in the discharge -probability and stage-flow rating is explicitly incorporated. The long term risk (probability of exceedance within the 50 year project life) is calculated directly from the expected annual exceedance probability using the binomial theorem. Event performance is the conditional probability of the project containing a specific event, should it occur. These values are a direct output of the risk-based analysis.

Inspection of performance results indicate only the 8 m. high levee affords a high level of performance. This is

both the expected annual exceedance and event performance through the chance of containing the .4 percent chance event. Since it also provides maximum net benefits it appears to be a logical choice from the federal perspective. Notice, however, it has a 14 percent chance of exceedance during its project life. Since the consequences of capacity exceedance vary for different types of projects it is an important consideration in plan selection. Capacity

Table 2. Results of performance evaluation

Plan description	Expected annual exceed. prob.	Prob. of exceed. in 50 yrs	Event Performance, as %-chance non-exceedance for specified event		
			.02 Prob. event	.01 Prob. event	.004 Prob. event
W/out project	0.075	0.92	2.3	0.0	0.0
7 meter levee	0.012	0.46	88.2	48.3	6.6
8 meter levee	0.003	0.14	99.7	97.5	76.3
Channel	0.031	0.79	24.8	1.9	0.0
Detention	0.038	0.86	20.5	4.0	0.3

exceedance for levees may cause sudden deep flooding that results in high risk to occupants and significant damage. Channels and detention basins do not normally make matters worse when the capacity is exceeded. These considerations as well as others, such as environmental and social impacts, are requisites for plan evaluation and selection. Economic and performance information derived from risk-based analysis enable better decisions for project selection.

PROJECT STUDIES RISK PERFORMANCE RESULTS

Questions often arise with regard to the relationship between the Corps historic levee studies, risk-based analysis results, and certification of Corps' levees for FEMA base flood protection. Table 3 summarizes the results from several on-going Corps levee project investigations. Note that the NED plan levee elevation, the project which is most often recommended for implementation, is not related to, nor dependent upon, the FEMA certification elevation.

RISK-BASED ANALYSIS AND THE DESIGN PROCESS

A Risk-based Analysis is only one component of a much larger process in a flood damage reduction study. While this analysis provides a wealth of information that was not previously available, it is not a substitute for good engineering practice, nor is it intended to be. The

Table 3. Corps levee project risk-based analysis results

General Information		Risk-based Analysis Results				
(1) Levee Project	(3) FEMA Cert. Elev. (Ft.)	(4) NED Plan Elev. (Ft.)	(5) NED Levee Expected Prob.	(6) 1% Chance Expected Elev. (Ft.)	(7) Conditional % Chance Non-exceedance	
					FEMA (Col. 3)	NED (Col. 4)
1. Pearl R., Jackson, MS	44.6	47.0	0.0013	41.8	97.6	99.8
2. American R., CA	49.1	52.0	0.0046	47.1	83.0	93.4
3. West Sacramento, CA	32.2	33.5	0.0006	29.8	99.9	99.9
4. Portage, WS	798.3	797.0	0.0001	795.6	99.9	99.6
5. Grand Forks, ND	834.4	NA	NA	831.5	90.8	NA
6. Hamburg, IA	912.2	911.5	0.0011	909.8	99.9	99.2
7. Pender, NE	1329.3	1330.0	0.0026	1327.8	76.3	83.6
8. Muscatine, IA	560.8	561.5	0.003	558.8	90.1	94.4
9. Cedar Falls, IA	864.7	866.0	0.0028	862.6	90.0	94.0
10. Guadalupe R. TX	57.9	56.5	0.01	56.5	87.2	73.6
11. White R. IN	715.0	713.2	0.004	712.3	98.0	86.1

Column Definitions: (3) 1% chance median discharge + 3.0 feet. (4) The NED plan levee elevation. (5) The expected annual exceedance probability of the NED levee elevation. (7) The % chance non-exceedance of a levee with the top elevation equal to that corresponding to the column noted given the 1% chance median annual event occurs.

risk-based analysis discussed in this paper is used to formulate the type and size of the optimal structural (or non-structural) plan that will meet the study objectives. Corps' policy requires that this plan be identified in every flood damage reduction study it conducts. This plan, referred to as the National Economic Development Plan (NED), is the one that maximizes the net economic benefits of all the alternatives evaluated. It may or may not be the recommended plan based on additional considerations.

The first step in a flood damage reduction study is to conduct the risk-based analysis. This analysis identifies the NED Plan and provides a starting point for the design process. Output from the analysis includes data on stage exceedence probabilities and expected project performance at index locations along the stream.

A residual risk analysis for the NED Plan is next performed to determine the consequences of a capacity exceedence. We know that for a flood damage reduction project, the question is not **IF** the capacity will be exceeded, but what are the impacts **WHEN** that capacity is exceeded, in terms of both economics and the threat to human life! If the project induced and/or residual risk is unacceptable, and a design to reduce the risk cannot be developed, other alternatives must be further analyzed. Either a larger project, that will assure sufficient time for evacuation, or a different type of project, with less residual risk, should be selected to reduce the threat to life and property.

When the type and size of the project have been selected, we are ready to begin the detailed design. To attain the confidence that the outputs envisioned in the formulation of the selected project will be realized, specific design requirements are developed. For a levee, increments of height are calculated to provide for embankment settlement and consolidation, allow for construction tolerances, and permit the building of a road along the crown for maintenance and access during flood fights. For a channel project, super-elevation, if required to contain the design water surface profile, is determined. For a reservoir, allowances to accommodate the Inflow Design Flood without endangering the structure and to account for wind and wave action are estimated. A similar thought process is also used for upstream diversion projects. These specific requirements must be included in the design.

The design must also include measures to minimize the adverse impacts of a capacity exceedence. For levees, the final grade is set so that initial overtopping will occur at the least hazardous location along the line of protection. This location is usually at the downstream end of the levee, so the protected area will fill in a gradual manner. This

same approach is taken in the final design of channel projects. For reservoirs, a plan is developed so that as the point of capacity exceedence is approached, there is a gradual increase in outflow from the project to provide time to initiate emergency measures downstream. Upstream diversions are also configured to allow a gradual increase in flow during a capacity exceedence. These design efforts notwithstanding, it is normal practice to include a flood warning system in the final plan as a last measure for risk reduction.

Design of a flood damage reduction project places a special responsibility on the engineer because of the potentially catastrophic consequences of a capacity exceedence. Of the types of structural projects usually considered in a flood damage reduction study, a levee is by far the most dangerous due to the severe consequences that may result from overtopping. If a levee cannot be designed to assure gradual filling of the protected area when the capacity is exceeded, then it simply should not be built. Reservoirs, channels and upstream diversions are generally better structural choices than levees. They provide some measure of protection even after their capacity is exceeded, and, they are better suited to minimize the adverse impacts of a capacity exceedence because they can be designed and/or operated to effect a gradual increase in flows and inundation in the protected areas.

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